IE-82-01

Luminance of Road Surfaces for Fixed Highway Lighting Design and the Ontario Road Reflectance Matrix Photometer (ORRMP)

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Published for RTAC Annual Meeting, September 1982, Halifax

Published by:
The Policy Planning and Research Division
Ontario Ministry of Transportation and Communications
Hon. James W. Snow, Minister
H.W. Gilbert, Deputy Minister

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The Editor
Research and Development Branch
Ministry of Transportation and Communications
1201 Wilson Avenue
Downsview, Ontario
M3M 1J8

January, 1982
Revised June, 1982

ABSTRACT

The driver's visual needs at night are more closely related to the luminance of the road surface than to illuminance. Luminance is the reflected light towards the driver's eye, or the measured brightness. Illuminance is the incident light independent from the driver's view. Standards of luminance are being introduced into lighting design standards (IES) for highways and expressways. This implies a need for more knowledge on the light reflectance of pavement surfaces. Under the joint sponsorship of the Ontario Ministry of Transportation and Communications and Transport Canada, the University of Toronto has developed The Ontario Road Reflectance Matrix Photometer (ORRMP) equipment for reflectance measurements.

Reduced reflectance coefficients are measured on standard 15 cm (6 inch) core surface samples with automatic control of angular positions of pavement sample and calibrated light source. Several samples from the same surface must be measured and averages of the measured values must be calculated, in order to classify a particular pavement surface. The ORRMP equipment will enable highway authorities to classify their pavements with regard to the reflectance classes now being used in the emerging luminance methods of design.

The paper discusses the concepts of road surface luminance and reflectance coefficients to be measured. It then describes the University of Toronto equipment, including information on the accuracy of measured quantities which are: 1) tabulated reduced reflectance coefficients, r; and 2) reflectance parameters, Q0, S1, S2, in accordance with CIE recommendations.

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1/ INTRODUCTION

Electronic computer usage in roadway lighting design has not only resulted in faster and better performance of design work, but has triggered several innovations directed towards standards which are more closely related to driver visibility. These standards, although not yet finalized and still under discussion, use the physical concept of road surface luminance (i.e., measured or quantified brightness) either directly, or indirectly in connection with contrast, "visibility index", or similar concepts.

Therefore, it is necessary to acquire knowledge and collect specific data on roadway luminance. To do this, the Comite International d'Eclairage (CIE) has recommended methods and instrumentation for measurements which are the subject of this report.

For the purpose of lighting design (because actual road surface luminances fluctuate according to weather conditions and vary with surface texture), luminance functions as measured on surface samples are grouped into classes of reflectance and specularity, to be used in standard design work.

Such classes are determined by ranges of reflectance parameters and differ significantly for dry and wet surfaces. The recommended instrumentation can be used for two tasks, namely, for developing a classification system and for actual classification of pavement types.

This report contains a description of an instrument built by the University of Toronto's Electrical Engineering Department, in accordance with concepts developed by CIE. The instrument is called the Ontario Road Reflectance Matrix Photometer (ORRMP).

2/ LUMINANCE CONCEPTS

Lighting design methods of past decades were based on illuminance (i.e., incident light). It was easy to calculate road surface illuminance based on road geometry, luminaire layout, and luminous intensity functions, $I(\phi, \gamma)$. (Refer to Figure 1 and Equations 1 to 3.) Values of illuminance, E_p, measured in lux, must be added up at each grid point, P, from all contributing luminaires. Arrays of such grid points can be defined and values processed by electronic computation. Manual calculations were simplified by using precalculated utilization curves issued for each luminaire. On the other hand, the luminance method is more dependent on electronic computers.

Luminance is calculated from the corresponding illuminance values for the same grid points, P, but only that portion of the light which is reflected towards the driver's eyes is considered. As shown in Figure 2, the illuminance contribution, E_p, from each luminaire is multiplied by a coefficient, q, which depends on the light reflection properties of the pavement surface. For each driver position, or each lane, the calculated luminance arrays are different (unlike the illuminance arrays which remain the same). These luminance concepts were first developed in Europe [1, 2].

The reflection of light from road surfaces ranges from complete specularity (mirror effect) when the surface is flooded with water, down to almost complete diffusion for a non-glossy dry pavement. It was found that dry or almost dry conditions prevail most of the time and that the increase of glossiness for damp pavements usually increases the average luminance. The difference between average and minimum luminance is also increased, with a corresponding decrease in uniformity and visibility. It is difficult to take all this into account. Therefore, it is generally agreed that highway lighting should be designed and evaluated for dry (or, eventually, moderately wet) pavements. This permits the degree of glossiness of dry pavements to be classified into a few standard categories. The number of these categories would increase considerably if moist pavements were included.

On wet pavements, visibility, although diminished, is provided by the familiar blurred and streaky image of the luminaires reflected on a background of dark, wet pavement surfaces. Under these conditions, laterally extended light sources, such as fluorescent or low-pressure sodium luminaires, installed above the roadway render improved visibility because they generate wider streaks of blurred images.

As illustrated in Figure 2, the luminance coefficient is a function of four angles α, β, γ, and δ of the average brightness, which depends on the colour and texture of the pavement surface. Thus:

$$L = q(\alpha, \beta, \gamma, \delta) \times E_p \qquad (4)$$

where:

q = luminance coefficient, in $\frac{cd/m^2}{lux}$ being a function of the angles α, β, γ, and δ, for each particular pavement surface.

E_p = illuminance, according to Equation 3, in lux.

The measuring units of the aforementioned terms can be explained as follows. The luminance coefficient, q, is defined as the factor by which the illumination, E_p, (lux or lm/m^2) must be multiplied in order to obtain the luminance, L, (cd/m^2). In the metric system, the luminance coefficient is expressed in $\frac{cd/m^2}{lux}$, with a maximum value for a perfect white diffuser of $q_{max} = 1/\pi = 0.318$.

Values of luminance must be calculated for each luminaire and then added together. The luminance created by one luminaire at a given point (subscript i) according to Equation 4 is:

$$L = q\ (\alpha_i, \beta_i, \gamma_i, \delta_i,)\ E_p\ (\phi_i, \gamma_i) \qquad (4)$$

This is in accordance with Figure 2.

Adding the values for n luminaires, substituting Equation 3 for E_p, neglecting the influence of δ, and setting $\alpha = 1°$, the following equation for luminance is obtained:

$$L = \sum_{i=1}^{n} q(\beta_i, \gamma) \frac{I\ (\phi_i, \gamma_i) \cos^3 \gamma_i}{h^2} \qquad (5)$$

In conjunction with the work that went into the CIE recommendations, standard reflectance tables have been established in the form of reduced coefficients $r = q \cos^3\gamma$ for $\alpha = 1^{\circ}$. This combination of $\cos^3\gamma$ and q simplifies the reflectance measurements. Also, the combination $r = q \times \cos^3\gamma$ leads to table values r, which decrease with increasing γ or $\tan\gamma$, whereas the pure reflectance function q alone increases tremendously (as illustrated in Figure 3) for β being equal to or close to zero.

The number of luminaires to be taken into account (n) should include a longitudinal distance of 12 x h or more, beyond the point P. Additional luminaires beyond this range contribute insignificantly. By substituting $r = q \times \cos^3\gamma$, Equation 5 can be rewritten as:

$$L = \sum_{i=1}^{n} \frac{I(\phi_i, \gamma_i)\, r(\beta_i \tan \gamma_i)}{h^2} \qquad (6)$$

3/ REFLECTANCE COEFFICIENTS, q VERSUS r

The value q is the direct or straight luminance coefficient in reference to Equation 4; refer also to Reference 6 an Figure 3.

The value r is the reduced luminance coefficient for roadway lighting as recommended by CIE [4], reduced by the factor $\cos^3\gamma$ so that

$$r = q \cos^3\gamma \qquad (7)$$

There are two basic reasons for using r instead of q directly.

1) Firstly, for values of the incident angle γ close to 90° (and, at the same time, the angle β being close to zero), the direct coefficient q may become excessively large for more or less specular surfaces (Figure 3) whereas $\cos^3\gamma$ becomes a very small quantity. Thus, it is easier to tabulate the reduced coefficient r which always decreases with increasing γ, up to or close to 90°.

2) Secondly, the reduced coefficient can be measured directly by using the simple feature of a standard lamp running along a horizontal rail mounted under the ceiling, which is more practicable and less expensive than a circular goniometric arrangement (refer to Figure 4).

4/ PRINCIPLE OF MEASURING THE REDUCED LUMINANCE COEFFICIENT r

Referring to Figure 4, the lamp, S, moves along the rail, A-B, at a constant height, h, above the horizontally placed sample, P. A luminance meter at M measures the luminance at P and is rotated simultaneously with the sample around the axis AA'.

For a particular turning position of the sample (angles β and δ in Figure 2), and for a particular location of the lamp (tan γ) the luminance, L, is measured in the direction of M, with $\alpha = 1°$. The lamp, S, has a constant luminous intensity, I, always directed towards P.

In accordance with Equations 3, 4, 5 and 7, the measured value of luminance, L, is:

$$L = \frac{Ir}{h^2} \tag{8}$$

From this measurement r can be calculated

$$r = \frac{Lh^2}{I} \tag{9}$$

If the direct value of luminance coefficient, q, is needed, the value r can be converted to q by means of Equation 7, namely:

$$q = \frac{r\ (\beta,\ \tan\ \gamma)}{\cos^3\ (\gamma)} \tag{10}$$

It should be noted that the influence of δ is being neglected ($\delta = 0$), and α is being fixed at 1°, the assumed approximate angle of viewing of a car driver ahead and down to the road surface (assumed eye level: 1.5 m; viewing distance ahead: 86 m).

5/ CLASSIFICATION OF ROAD SURFACES

The results of measurements from a sample pertaining to a particular road surface is tabulated in terms of a function of $\tan\gamma$ and β which can be used as a design input after storing it as a computer memory array. Table 1 represents a typical array for a dark asphalt pavement surface. CIE-sponsored research in Europe has addressed the question of classifying such measurements into a manageable number of specularity classes. Usually there are four classes for dry pavements (some suggestions go as far as eight in this category). More recently, there has been work done on four additional classes pertaining to wet pavement surfaces [3, 5].

The most commonly known dry classes are designated as RI, RII, RIII, and RIV, and an alternative system is known as N1, N2, N3 and N4 -- all proposed for European-type pavements [4, 7]. In the U.S. and Canada the same or similar classes may apply, which will be subject to some research investigations. The example in Table 1 is RIII.

Classification of measured road surfaces is carried out by using certain parameters, which are Q0 (or q_0), S1 and S2, where

Q0 or q_0 = average luminance coefficient over a defined roadway ground area or space angle.

$$S1 = \frac{r(0,2)}{r(0,0)} \quad \text{(i.e., } \beta = 0, \tan\gamma = 2; \text{ and } \beta = 0, \tan\gamma = 0\text{)}$$

$$S2 = \frac{Q0}{r\,(0,0)}$$

The value Q0 can be understood as a parameter correlated to the average brightness of the pavement surface. The values S1 and especially S2 are parameters indicating the degree of specularity.

It is stipulated that surfaces with identical parameters are equivalent, with very little differences in the remaining r values, as measured and tabulated in the format of Table 1.

6/ INSTRUMENTATION FOR REFLECTANCE MEASUREMENTS AT THE UNIVERSITY OF TORONTO (ORRMP)

Following is a description of the Ontario Road Reflectance Matrix Photometer for reflectance measurements as designed and built at the University of Toronto's Department of Electrical Engineering [9].

The ORRMP system is designed to accept and measure reflectance matrices (r-values) of 15 cm (6 inch) circular (disk-shaped) samples of pavement surface courses, because they can be taken from road surfaces with standard equipment and easily shipped to the University of Toronto facility.

The instrumentation is automated and computer-controlled for one run of a sample (i.e., after placing and levelling the sample (Figure 8), all movements to various angular positions, the various measurements and their processing to r-values and parameters (Q0, S1, S2) are controlled by the computer until the run on the sample is completed).

Figures 5, 7, and 8 show a sample placed and levelled on a platform or turntable which rotates through all angular positions, β, in accordance with Table 1. The photo-multiplier detector shown in Figure 7 is rigidly attached to the rotating platform. Its power supply underneath (not attached to the turntable) is also shown in Figure 7.

The detector measures luminance at a viewing angle, α, successively for each of the angular positions, β, and (tan γ). The latter position is determined by the movement of the light source (Figures 9 and 10) along a horizontal rail, up to a maximum of tan γ = 12, at a distance of about 8.5 m.

The calibrated light source with a controlled power supply has a constant luminous intensity, I, and it stops at each of the white markings at electronically-controlled, accurate positions, corresponding to the (tan γ) entries in Table 1. Simultaneously, the assembly of the light source rotates in such a way that the slit for the light beam is always directed towards the sample. The curled cable supplies the electric power and the computer interface for lamp position control. The height of the light source above the sample is 0.64 m.

Figure 5 illustrates the console beneath the turntable. It shows the power supply for the light source and the various computer interfaces which control the automatic processes during a measurement run.

Figure 6 shows the micro-computer, the printer, and a tape recorder for memory output.

In order to minimize reflections, most parts of the equipment and the walls of the room are painted in matte black (which does not show on the photographs).

7/ PROCEDURE FOR DETERMINING A REFLECTANCE MATRIX WITH U OF T EQUIPMENT (ORRMP)

The sample size of 15 cm (6 inch) diameter was chosen because it is the most common and readily available dimension of core samples from asphalt or concrete (Figure 11). This is a small size, and the field of view of 8 cm by 4 cm within the 15 cm circle is much smaller than the CIE recommended field of view (minimum 20 cm by 5 cm) [4, 7]. This fact causes deviations due to irregularities of coarse textures for each sample measurement with the U of T ORRMP equipment. In order to achieve a similar degree of accuracy as that achieved with typical CIE measuring equipment, statistical averages must be established for several independent measurements. This means that for one particular pavement surface having a fairly uniform coarse texture, several core samples must be provided and submitted for measurement.

Each sample can be used for two independent measurements by shifting the field of view left and right of the centre as shown in Figure 12. A preliminary statistical analysis on three samples with six independent measurements resulted in standard deviations from the average values of Q0, S1 and S2 of about 5% or less, for typical coarse asphalt pavements. The degree of accuracy indicated here should be sufficient for any routine classification work. However, for more scientific investigations, larger sample sizes would probably be necessary.

8/ PILOT MEASUREMENTS FOR ONTARIO PAVEMENTS

8.1/ The Test Sections

The Lindsay test sections [10] were chosen to carry out pilot measurements on pavements of known composition. About 20 samples were measured from various sections, and each sample was measured at least three times in slightly changed angular position (+5°, 0°, -5°). Comparing the results with the Erbay Atlas data, it was found that in terms of specularity (S1) the surfaces range from S1 = 0.49 to S1 = 1.45, i.e., from below the standard surface R2 to above R3. The most specular surfaces contain at least 60% limestone coarse aggregates, and the least specular surfaces contain more than 70% igneous rocks. In the latter, the igneous stone projections feel gritty; in the former, the limestone projections feel smooth and polished. The surfaces were exposed to moderate traffic from summer, 1978, to fall, 1980.

The test sections had been skid tested by the old, non-standard MTC skid trailer in summer, 1980. In Figure 13 the skid numbers, SN, from these tests are plotted versus the specularity parameter, S1.

There is a weak negative correlation (-0.64) between the skid number, SN, taken at 80 km/h and the parameter, S1. Stronger correlations may be expected between low speed or "zero speed" skid numbers and S1.

In any case, it is certain that the degree of specularity of pavement surfaces is related to the degree of smoothness or polish of coarse aggregates.

8.2/ The Samples

The samples were from different test sections. Nevertheless, a statistical analysis was performed to evaluate the repeatability of results on different parts of the same surface. Beyond the two independent runs on one sample on the fields of view shown in Figure 12, percentage deviations of normalized parameters were calculated, based on six runs on three samples. The standard deviations were found to be below 5%. This

seems to establish the reliability of a procedure of measurement based on statistical averages from six fields of view and three samples taken from the same pavement.

Finally, a sample of 20 specimens (cores) was taken from a typical HL1 pavement with traprock coarse aggregate. A statistical analysis was carried out for long range and short range variance of reflectance parameters (Q0, S1, S2). "Long range" means over a considerable stretch of the wheel path, and short range means that which can be expected from several closely spaced fields of view as shown in Figure 12. Based on this sample, 95 percent confidence limits were calculated for three samples or six rims. They are as follows:

	Close Range	Long Range
Q0	± 3%	± 11%
S1	± 5%	± 12%
S2	± 4%	± 6%

For three samples or six rims there is a probability of 0.95 that the population mean is within the range of the sample mean plus/minus the percentage margin indicated.

9/ APPLICATIONS OF THE U OF T EQUIPMENT (ORRMP)

Three potential applications of the U of T ORRMP equipment are immediately evident:

1) Verify or modify CIE classifications for Canadian and American design specifications of luminance method.

2) Classify currently used pavements in Ontario and other provinces or states.

3) Study the influence of variation in viewing angle (which requires a modification of the equipment).

Items 1 and 2 are interrelated development projects, already initiated. Item 3 is important with regard to the question of variations in vehicle sizes as small or compact cars typically have eye levels lower than 1.5 m, and commercial vehicles have eye levels which are much higher above the ground. All these are obvious projects related to the luminance design concept. Other possible uses of the instrumentation are as follows.

4) Luminance measurements in conjunction with visibility studies on lane markings, where the viewing angle is equal to α or similar.

5) Comparative measurements in conjunction with the goniometric-type reflectance measurements intended to be carried out in the U.S., which are based on q, not r.

Finally, the main purpose of the aforementioned classification work is to obtain more accurate data for the pavement reflectance characteristics which are used in the new methods of lighting design by luminance [7,8].

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TABLE 1

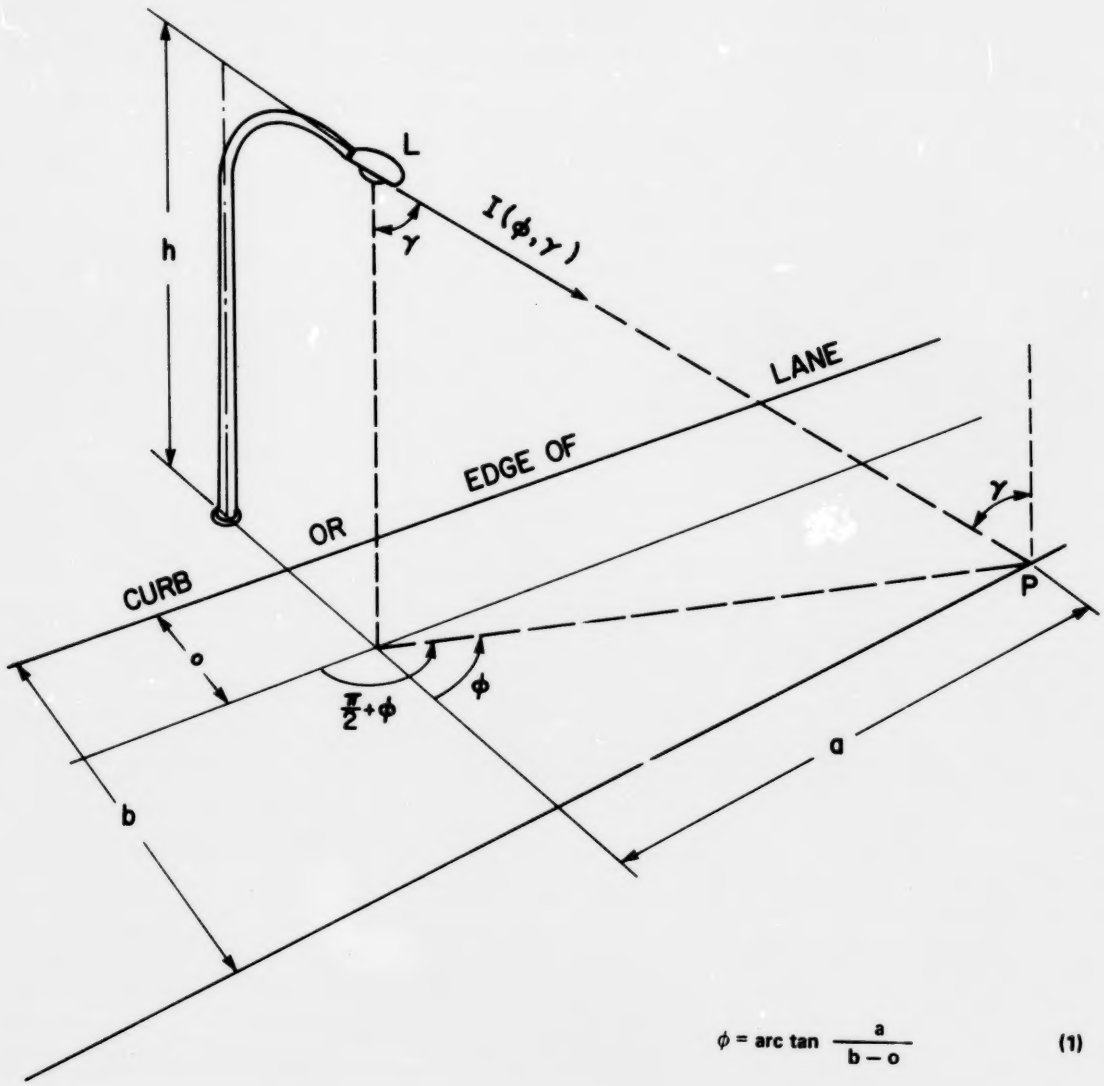
STANDARD REFLECTION TABLE R-III

TABLE OF REFLECTANCE DATA: $q \cos^3\gamma \times 10^4$

tan γ \ β°	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294
0.25	326	326	321	321	317	312	308	308	303	298	294	280	271	262	258	253	249	244	240	240
0.5	344	344	339	339	326	317	308	298	289	276	262	235	217	204	199	199	199	199	194	194
0.75	357	353	353	339	321	303	285	267	244	222	204	176	158	149	149	149	145	136	136	140
1	362	362	352	326	276	249	226	204	181	158	140	118	104	100	100	100	100	100	100	100
1.25	357	357	348	298	244	208	176	154	136	118	104	83	73	70	71	74	77	77	77	78
1.5	353	348	326	267	217	176	145	117	100	86	78	72	60	57	58	60	60	60	61	62
1.75	339	335	303	231	172	127	104	89	79	70	62	51	45	44	45	46	45	45	46	47
2	326	321	280	190	136	100	82	71	62	54	48	39	34	34	34	35	36	36	37	38
2.5	289	280	222	127	86	65	54	44	38	34	25	23	22	23	24	24	24	24	24	25
3	253	235	163	85	53	38	31	25	23	20	18	15	15	14	15	15	16	16	17	17
3.5	217	194	122	60	35	25	22	16	16	15	13	9.9	9.0	9.0	9.9	11	11	12	12	13
4	190	163	90	43	26	20	16	14	12	9.9	9.0	7.4	7.0	7.1	7.5	8.3	8.7	9.0	9.0	9.9
4.5	163	136	73	31	20	15	12	9.9	9.0	8.3	7.7	5.4	4.8	4.9	5.4	6.1	7.0	7.7	8.3	8.5
5	145	109	60	24	16	12	9.0	8.2	7.7	6.8	6.1	4.3	3.2	3.3	3.7	4.3	5.2	6.5	6.9	7.1
5.5	127	94	47	18	14	9.9	7.7	6.9	6.1	5.7										
6	113	77	36	15	11	9.0	8.0	6.5	5.1											
6.5	104	68	30	11	8.3	6.4	5.1	4.3												
7	95	60	24	8.5	6.5	5.2	4.3	3.4												
7.5	87	53	21	7.1	5.3	4.4	3.6													
8	83	47	17	6.1	4.4	3.6	3.1													
8.5	78	42	15	5.2	3.7	3.1	2.6													
9	73	38	12	4.3	3.2	2.4														
9.5	69	34	9.9	3.8	3.5	2.2														
10	65	32	9.0	3.3	2.4	2.0														
10.5	62	29	8.0	3.0	2.1	1.9														
11	59	26	7.1	2.6	1.9	1.8														
11.5	56	24	6.3	2.4	1.8															
12	53	22	5.6	2.1	1.8															

Values tabulated with $Q_o = 0.07$

S1 = 1.11, S2 = 2.38

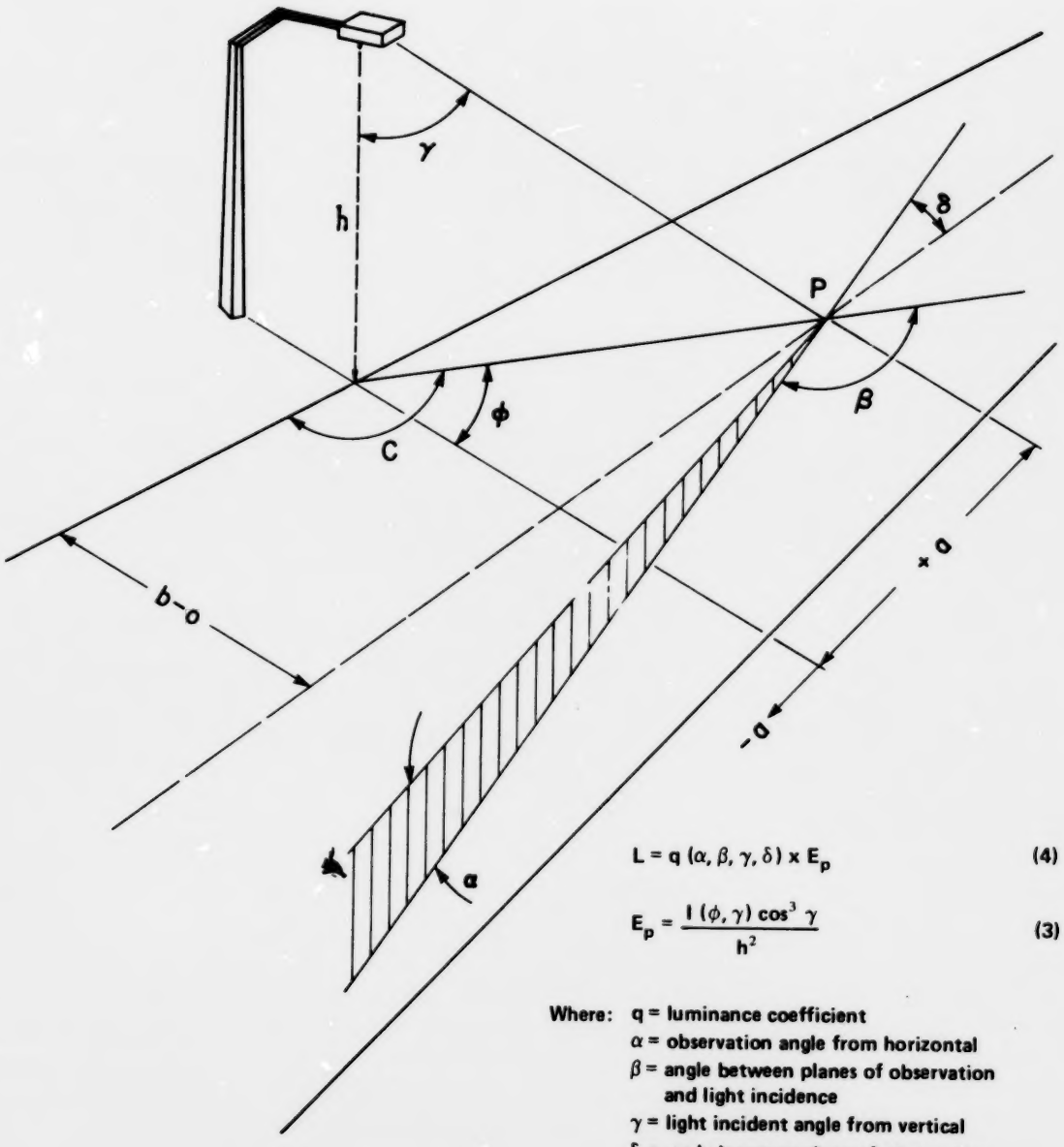


$$\phi = \arctan \frac{a}{b - o} \qquad (1)$$

$$\gamma = \arctan \frac{\sqrt{a^2 + (b - o)^2}}{h} \qquad (2)$$

$$E_p = \frac{I(\phi, \gamma) \cos^3 \gamma}{h^2} \qquad (3)$$

Figure 1/ Illuminance



$$L = q\,(\alpha, \beta, \gamma, \delta) \times E_p \qquad (4)$$

$$E_p = \frac{I\,(\phi, \gamma)\cos^3 \gamma}{h^2} \qquad (3)$$

Where: q = luminance coefficient
α = observation angle from horizontal
β = angle between planes of observation and light incidence
γ = light incident angle from vertical
δ = angle between plane of observation and road axis
ϕ and C as indicated

Figure 2/ Luminance

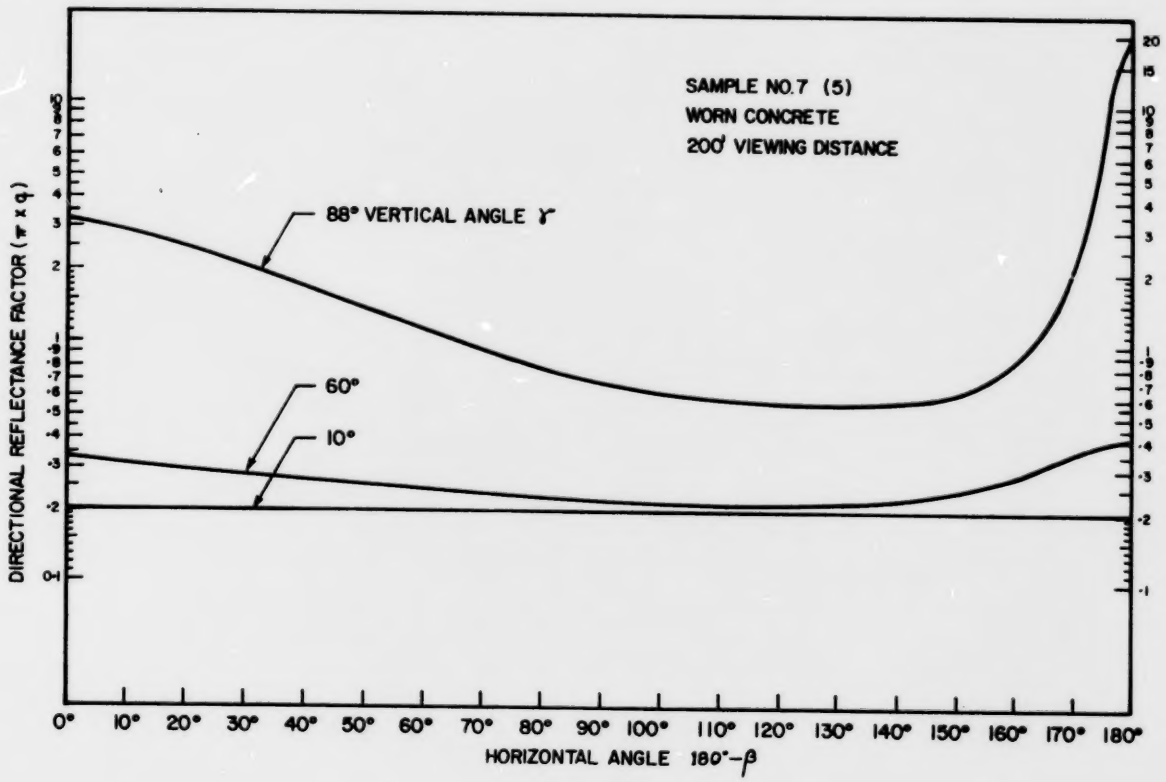

SAMPLE NO.7 (5)
WORN CONCRETE
200' VIEWING DISTANCE
88° VERTICAL ANGLE γ
60°
10°
DIRECTIONAL REFLECTANCE FACTOR (r x q)
0° 10° 20° 30° 40° 50° 60° 70° 80° 90° 100° 110° 120° 130° 140° 150° 160° 170° 180°
HORIZONTAL ANGLE 180°-β

Figure 3/ Reflectance Function According to E. King [6]

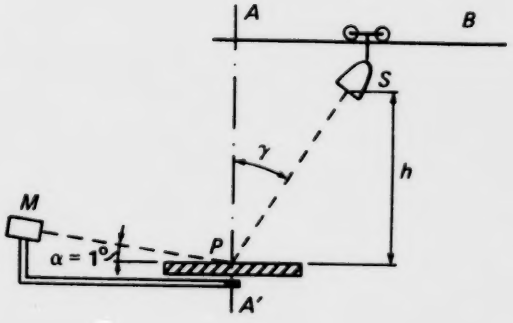


Figure 4/ Principle of an Experimental Set-up for the Measurement of the Reflection Properties of Road Surfaces

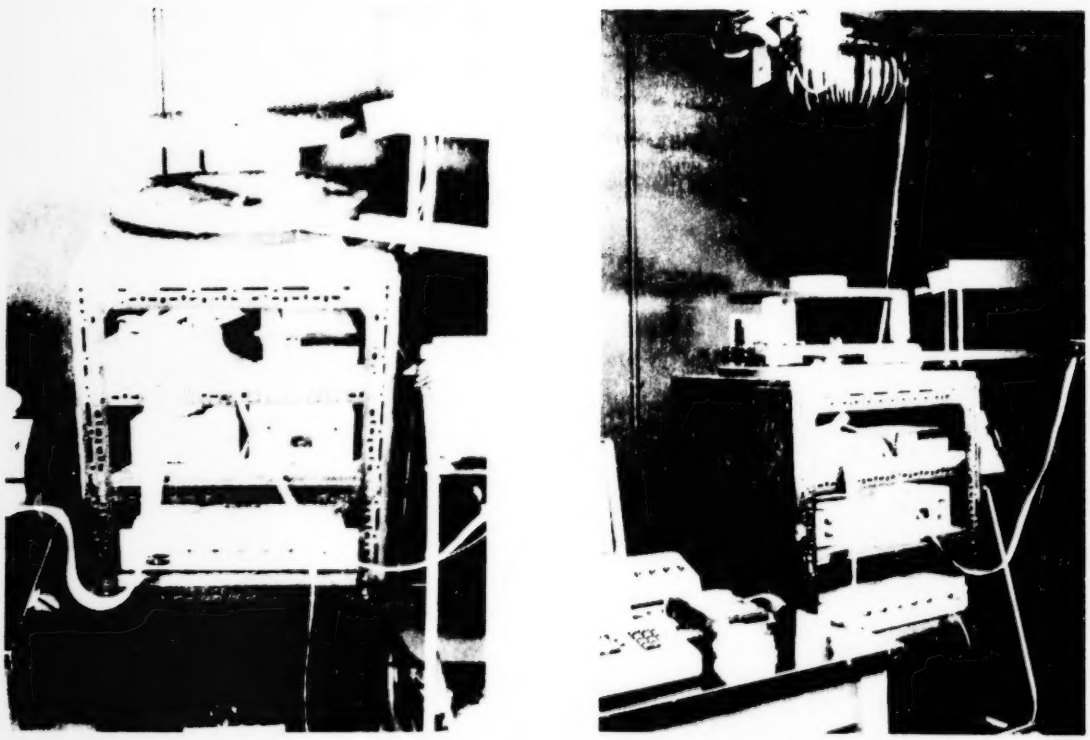


Figure 5/ Rotating Table with Sample and Electrical Controls

Figure 6/ Computer Terminal and Printout

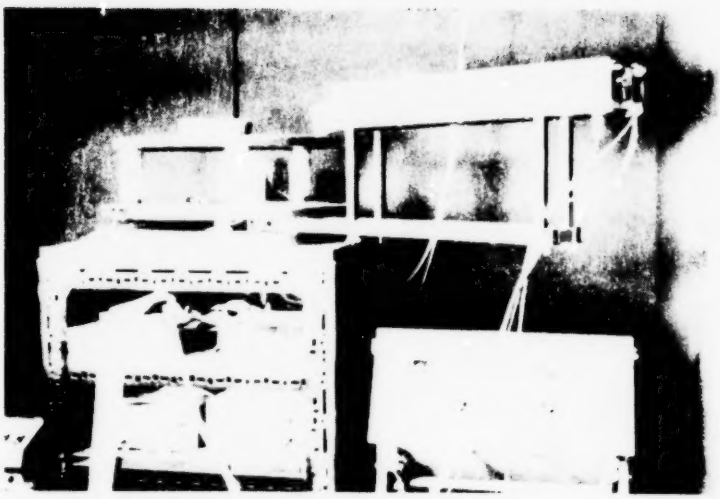


Figure 7/ Photomultiplier Detector Unit Attached to Sample Table

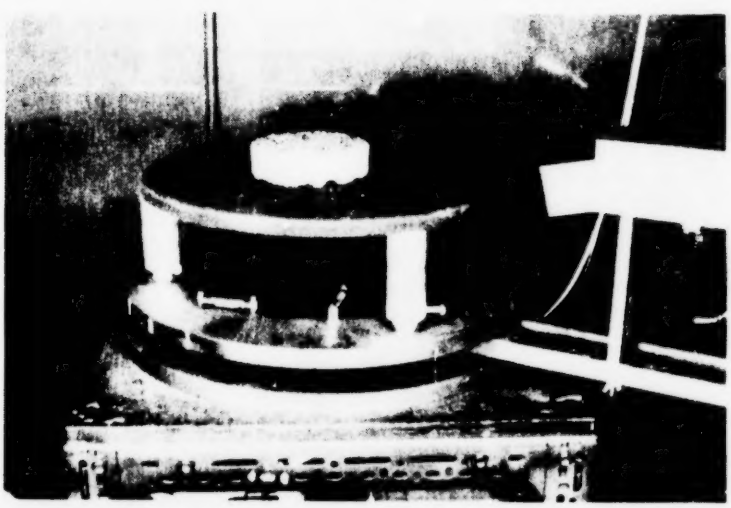


Figure 8/ Close-Up of Rotating Table with Sample

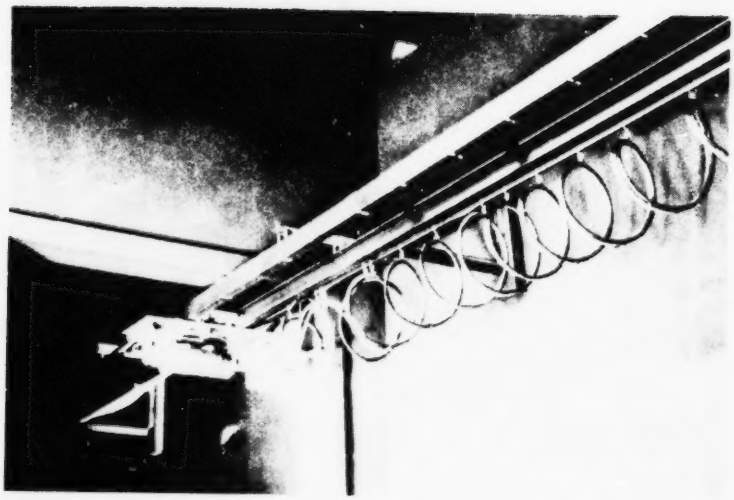


Figure 9/ Moveable Light Source and Track

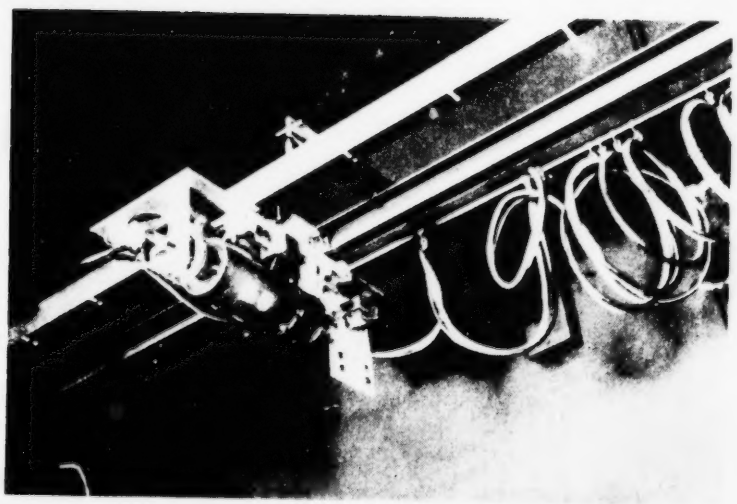
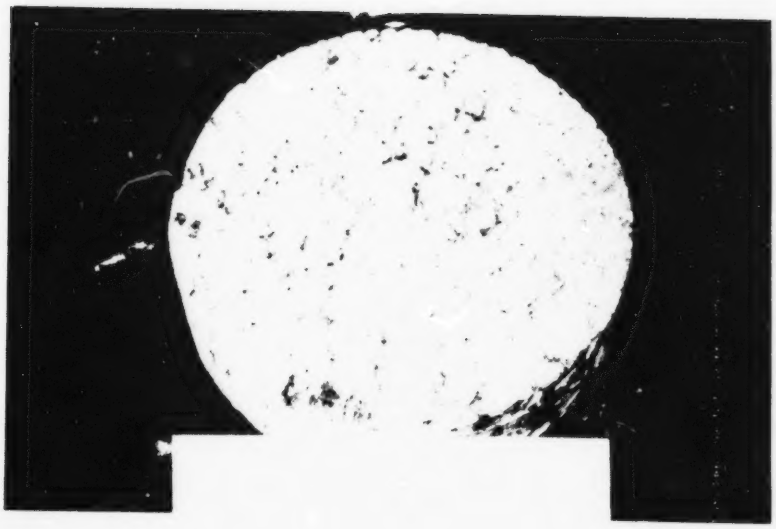


Figure 10/ Close-Up of Moveable Light Source



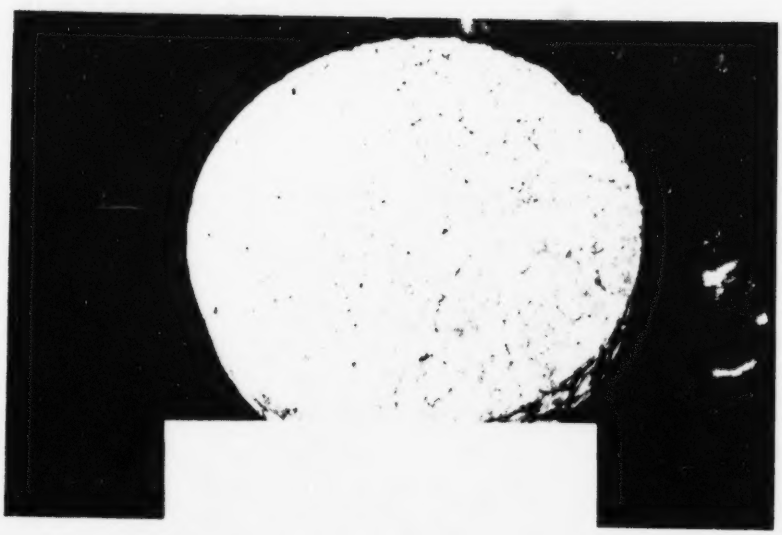


Figure 11/ Surface of Asphalt Samples

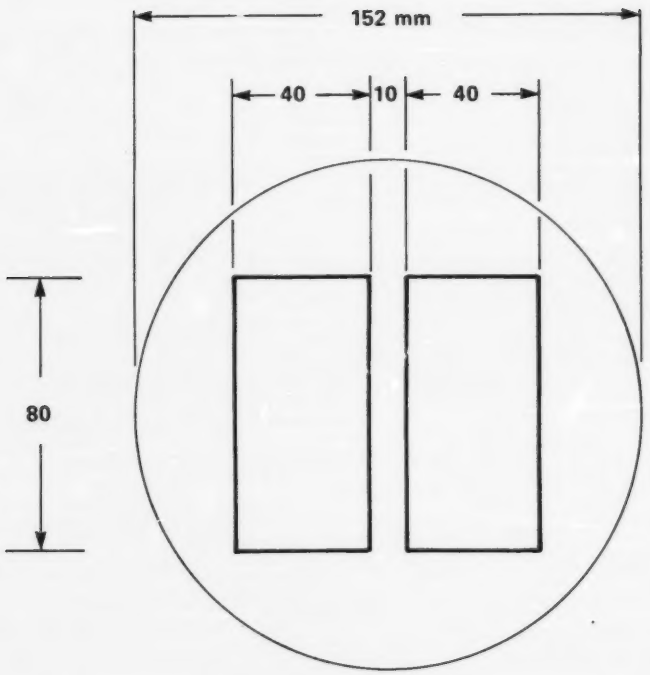


Figure 12/ Field of Views within Sample Surface

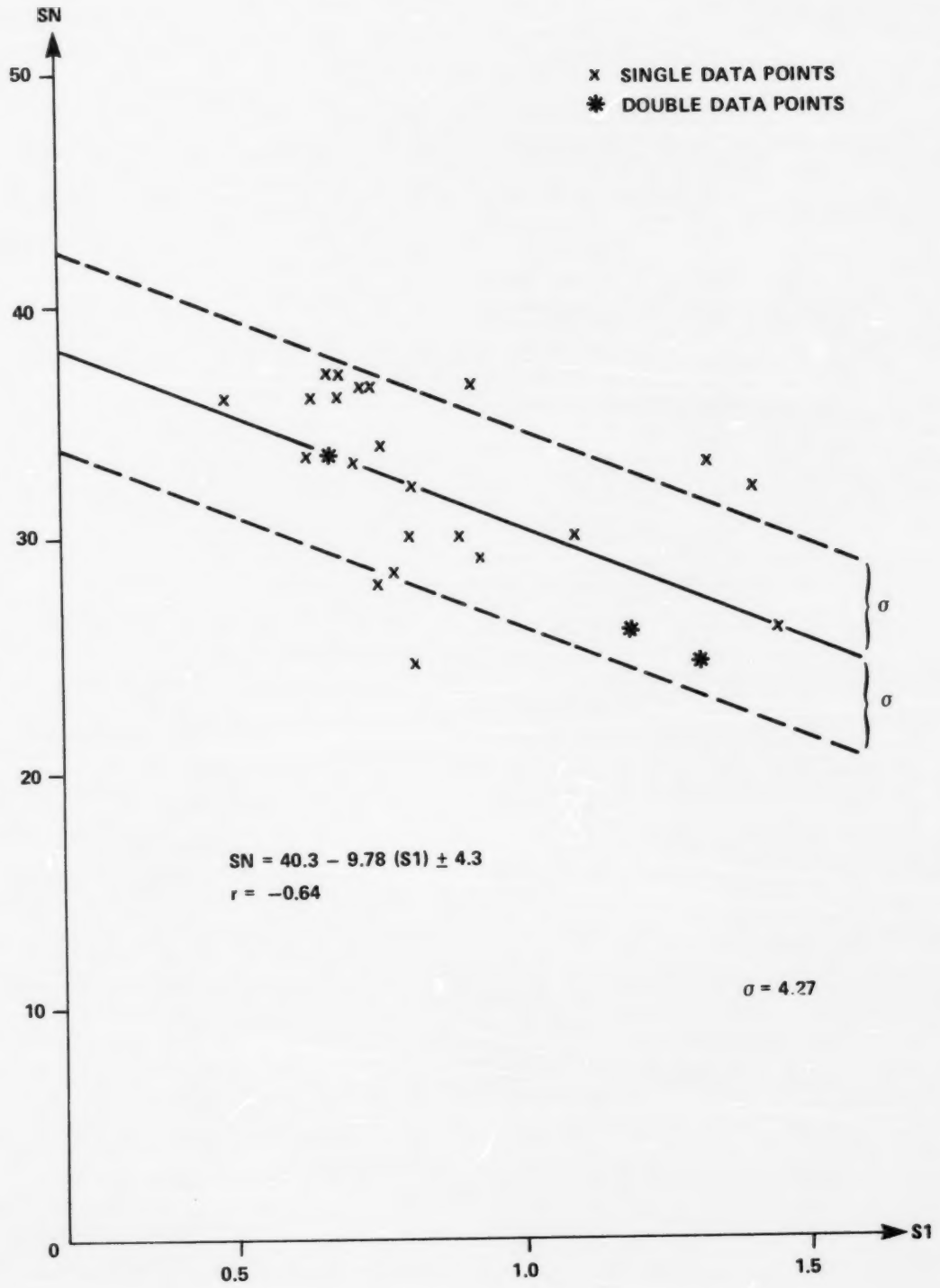


Figure 13/ Specularity Versus Skid Number